

Liquid – vapour surface sensors for liquid nitrogen and hydrogen*

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Tests of resistance thermometers as liquid – vapour interface sensors for LH_2 and LN_2 showed that most could be made to detect the liquid surface, but a tiny silicon sensor developed at NASA Goddard Space Flight Center gave the fastest response. Tests of a commercial optical surface sensor and two modified versions of it showed that optical sensors can reliably and rapidly detect the liquid – vapour interface of both hydrogen and nitrogen.

Keywords: space cryogenics; surface sensing; liquid – vapour interface

The objective of this study was to identify devices to serve as liquid – vapour detectors in zero gravity. In the early 1960s a number of liquid – vapour (L – V) interface sensing devices were tested in liquid hydrogen (LH_2)^{1–3}. Part of this work was done at the National Institute of Standards and Technology (then National Bureau of Standards) for NASA Lewis Research Center. The sensors tested were then commercially available and had various principles of operation. Differences in resistance, capacitance, light reflection, acoustic impedance or viscous damping indicated whether the sensors were in liquid or gas. Many of the sensors in these early tests were liquid level measuring devices. They resolved the liquid surface well in the vertical direction only.

Many new level gauging devices are commercially available today. Like the sensors examined in the earlier tests, they were mostly designed for making level measurements in normal gravity, and hence resolve position only along one axis. Often, the sensing element itself is large in the plane perpendicular to the one axis. In zero gravity, the L – V interface can be moving in any direction, so the L – V sensor must approximate a point sensor to resolve adequately the passing of an interface. Only sensors approximating point sensors were tested in this work – resistance thermometer types and optical types. Tests of a resistive sensor developed at NASA Goddard specifically for interface sensing are described here.

Three miniaturized versions of the optical level sensor tested in the 1960s were tested in this work. Optical

fibres coupled external sources and detectors to the sensors. One of the optical level sensing devices was a commercial unit. The remaining two sensors were built at this laboratory.

Test Apparatus

A diagram of the test apparatus is shown in *Figure 1*. The testing in LH_2 was done in a sealed glass Dewar system to eliminate any chance of mixing H_2 and air. Up to six sensors can be mounted on a holder. This holder was cycled rapidly up and down by a double acting air cylinder. The total travel is about 10 cm. Air cushions in each end of the cylinder bring the piston to a stop at the end of its travel. Hand operated valves controlled the motion of the sensor holder. The shortest cycle times used were under 1.5 s. The water driven cylinder serves to adjust the vertical position of the air cylinder and sensor holder so that the sensors pass through the liquid interface somewhere between the 2.5 and 7.5 cm positions of the air cylinder travel. A linear potentiometer connected to the drive cylinder shaft gives a voltage position signal. The position at which the sensors cross the interface can be determined either by placing the sensor at the liquid level and reading the position voltage or by noting the voltage at which a fast L – V sensor starts the transition from the gas signal S_g to the liquid signal S_l . The velocity of the sensor holder was about 3 m s^{-1} at the drive air pressures used. The transit time of the sensors through the liquid interface was less than 2 ms for most of the sensors tested.

The electrical leads are fastened to and guided by a thin steel strip which is attached to one end to a fixed point at the Dewar wall and the moving sensor holder on the other. The rolling loop allows the leads to follow the moving sensor holder.

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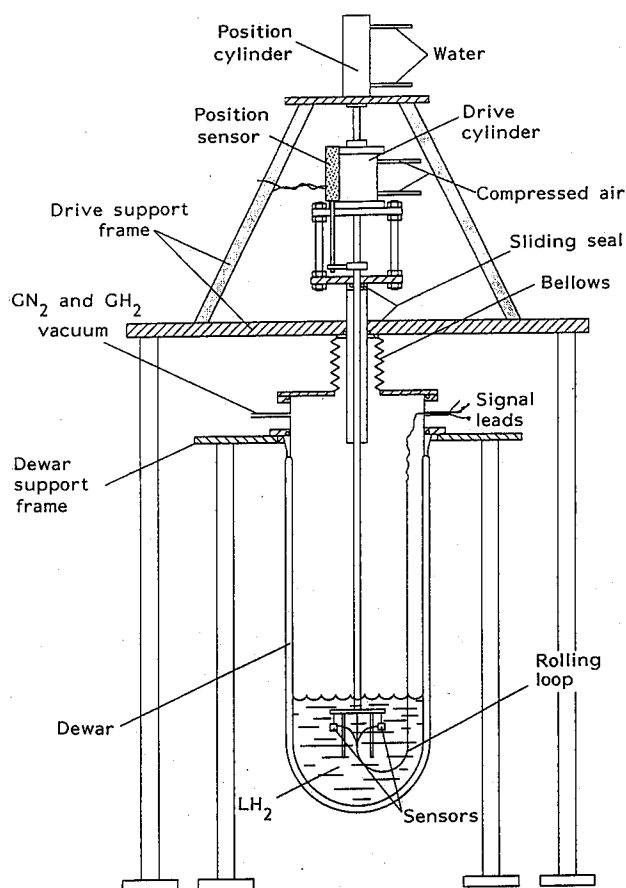


Figure 1 Liquid-vapour surface sensor test apparatus

The resistive sensor was powered by a constant current source. The voltage across this source was the sensor output signal.

The voltage signals from the L-V sensors and the position sensors were sequentially read by a fast 13-bit 8-channel multiplexer and analogue-to-digital converter card in a laboratory computer. The reading rate was 10^5 Hz. Since the reading rate never exceeded 2000 Hz channel, no reading delay correction was made. The lapsed time for each test run was limited by the amount of data that could be stored. For two data channels, 13 000 readings each was the maximum.

Resistance sensors were mounted on a stainless steel blade, $51 \times 17 \times 0.5$ mm in dimension. The sensor was centred in a 7 mm diameter hole punched near the end of the blade. The sensor was supported by its leads which were cemented to the blade. The blade was supported horizontally from the sensor holder from the end opposite the sensor.

Most of the tests were done with the leads to the sensor horizontal. One test in each LN_2 and LH_2 was done with the sensor mounted so the leads ran vertically down to the sensor.

The measurement time was added to the data files after the data were taken by multiplying the reading number by the reading period. The response times depend on the method of analysis. They were determined by computer analysis of the data using the liquid surface given by the position sensor voltage and

$(S_1 - S_2)/2$ as the sensor signal indicating the passage of the liquid level. The signal from the sensor was read as a voltage in this work. The response times could be shortened by differentiating between in and out events in the sensor signal instead of using one voltage to identify the transition.

Resistive sensor tests

The LVDG sensor, built at Goddard Space Flight Center, consisted of a 0.25 mm cube of doped silicon with each of the two leads attached to opposite faces. The design is that used for L-V interface sensors in the SHOOT experiment⁴. The doped silicon chip used in these tests was chosen by the Goddard staff for its high sensitivity at 20 K.

Figure 2 shows some results of rapid cycle testing of LVDG in LH_2 . For these tests the sensor was mounted with the leads horizontal relative to gravity and the direction of motion. The response times can be determined from Figures 3a and 3b, which show the first withdrawal from the liquid and return to the liquid. This is part of the data of Figure 2 redrawn on an expanded time scale. The time at which the sensor responded is chosen arbitrarily to be 3.95 V, the midpoint of the transition of the sensor signal which occurred at 0.409 s. The sensor crossed the liquid surface when the position sensor registered 1.9 V, which occurred at about 0.4075 s. The delay time was about 1.5 ms. From the estimated slope of the position sensor curve at 1.9 V, the velocity of the sensor through the liquid surface is over 3 m s^{-1} . The LVDG sensor passed through the liquid surface in less than 0.1 ms. The bounce in the position sensor is caused by the air cushion at the end of the stroke.

When the sensor moves from the gas to LH_2 , the sensor voltage at constant current starts increasing while the sensor moves in the gas, as Figure 3b shows. The sensor arrived at the liquid surface at about 1.2265 s. The midpoint of the steep slope in the sensor signal occurs a little more than 2 ms later. For the dozen cycles of the test shown in Figure 2, the average delay entering the fluid

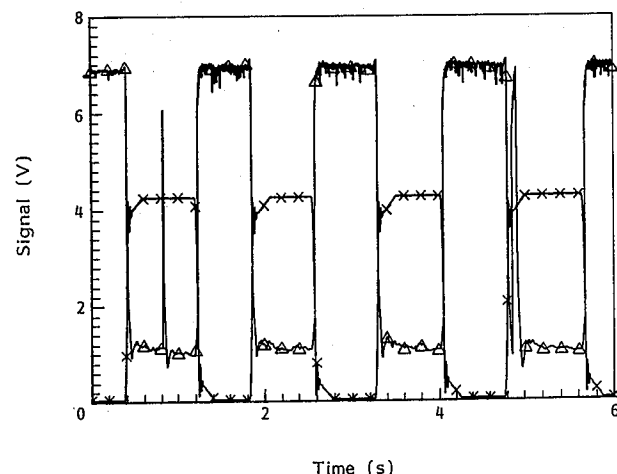


Figure 2 Δ , Output signal from LVDG cycled between LH_2 and GH_2 ; \times , position sensor voltage. Leads horizontal, $I = 9 \text{ mA}$, every 100th data point shown

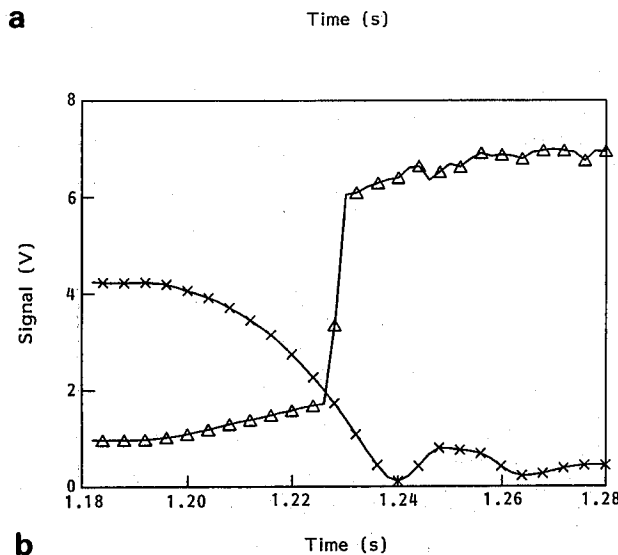
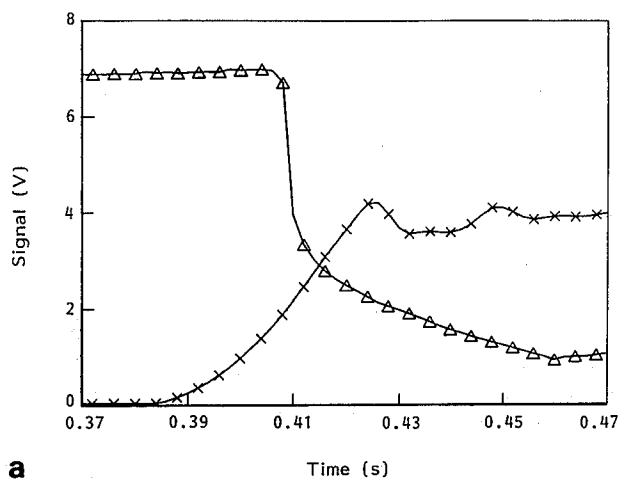


Figure 3 Δ , Output signal from LVDG at a transition from: (a) LH_2 to GH_2 ; (b) GH_2 to LH_2 . Data of Figure 2 on an expanded time scale. x, Position sensor voltage. Leads horizontal, $I = 9$ mA, every other data point shown

was 1.5 ms and the average delay leaving the liquid was 3.5 ms.

In Figure 2, occasional spikes in the sensor signal appear, both downward spikes when the sensor is in the liquid and upward spikes when the sensor is in the gas. The upward spikes may occur because of the splashing associated with the sensor holder passing through the liquid surface. The downward spikes may be caused by splashing, but they may also result from a momentary transition to film boiling on the sensor surface.

The signal change for this sensor is large at 9 mA, changing from about 1 V in the gas to 7 V in the liquid. When the sensor current is raised to 11 mA, the sensor voltage in the liquid becomes unstable, and drops periodically and briefly to nearly the gas value. At 20 mA, the in-liquid signal is uniformly noisy and the level has decreased to less than 4 V. The voltage level in the gas increases to about 1.5 V.

An approximate curve of resistance as a function of temperature for this sensor in the 20 K to 200 K region is shown in Figure 4. The wiggles in the curve between 80 and 120 K probably are caused by the low resolution

of the signal processing electronics. Figure 5 shows the resistance of the sensor in gas and in liquid as a function of the sensor current. The resistance (R) in the gas decreases rapidly with increasing current at lower currents but levels out above about 10 mA as would be expected for the $R(T)$ dependence, where T is temperature, shown in Figure 4. The resistance in the liquid decreases rapidly above about 10 mA current. The decrease of R in LH_2 with increasing sensor current results from the increase of temperature necessary to transfer the sensor power to the liquid. Above about 10 mA the heat flux to the LH_2 was sufficient to cause film boiling on the sensor surface. This reduced the heat

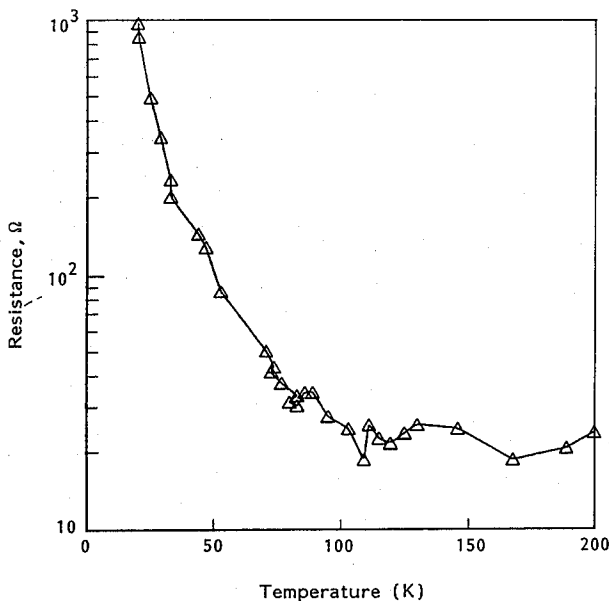


Figure 4 Δ , Resistance of LVDG as a function of temperature. Leads horizontal

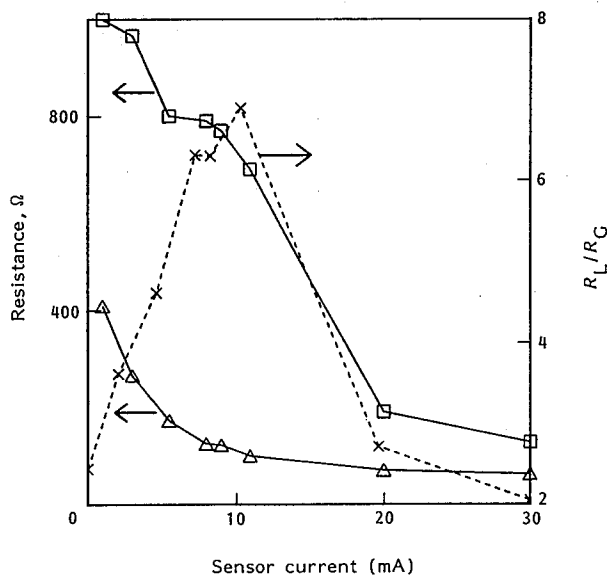


Figure 5 Resistance of LVDG as a function of current, in GH_2 (Δ) and in LH_2 (\square). R_L/R_G (x). Leads horizontal

transfer coefficient causing the sensor temperature to increase. The sensor resistance then decreased even more. The unstable behaviour observed at 11 mA was an oscillatory condition set up by the strong dependence of the sensor resistance on temperature.

The ratio of the resistance in LH_2 to the resistance out is included in Figure 5. This ratio is highest at 11 mA, where the sensor oscillation was first seen.

The response time is shown in Figure 6 for LVDG for the data of Figure 2 for the sensor both entering and leaving the liquid. Below 9 mA the response time leaving the liquid increases rapidly. At higher currents, the response time into the liquid starts increasing with increasing current. The sensor at high currents was heated so much above liquid temperature that a longer time was required to cool it back to liquid temperature.

When the LVDG sensor is supported by leads descending vertically to it from the holder, the average response time for LVDG upon entering the liquid was unchanged from that with horizontal leads. In half of the ten cycles recorded at 1 kHz a spike in the LVDG signal voltage reaching to the liquid reading occurred between the start of the sensor motion and the entrance to the liquid. The position sensor read 1.99 V at the crossing. The LVDG signal of 4.65 V was considered to be the transition point. In all but one of the remaining five tests, a precursor to the main transition of LVDG occurred.

The average response time leaving the liquid increased to almost 21 ms when the leads were vertical. The 21 ms response time was measured to the first response of the sensor to vapour. On about half the liquid-to-gas transitions, the LVDG signal cycled between the liquid and gas values for about 0.1 s after LVDG left the liquid. On the remaining half of the test cycles, the LVDG signal cycled back to the liquid reading as much as 0.3 s after the sensor departed the liquid.

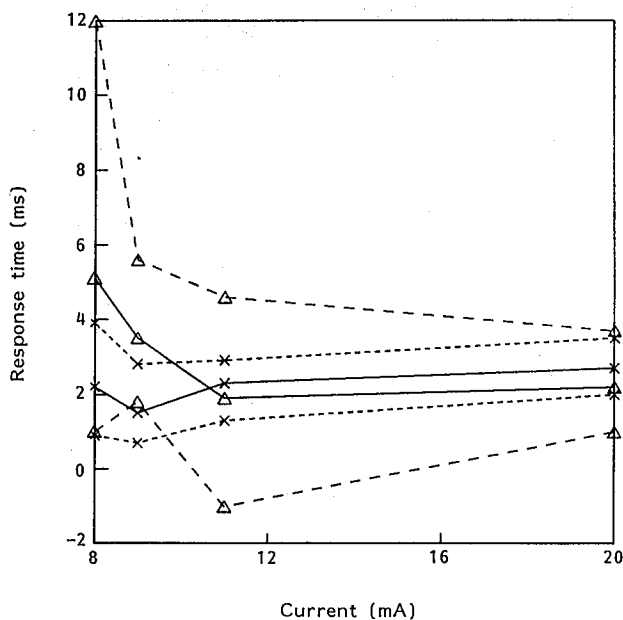


Figure 6 Computer analysed average response time as a function of current for the sensor: x, entering the liquid; Δ , leaving the liquid. Dotted lines show total data scatter

The increase of the in-to-out response time for the vertical lead configuration and the cycling after the initial response must be caused by liquid draining down the leads to the sensor from the holder. This source is probably enhanced by the fact that the insulation over the leads consisting of varnished paper had partially detached allowing liquid to enter the crack between it and the blade holding the sensor.

The starting position of the sensor relative to the liquid surface appeared to cause differences in the response time, at least for the vertical lead configuration. The measuring frequency of 50 Hz was too low to measure the out-to-in response accurately but the in-to-out response time is about 5 to 6 ms longer when the sensor holder has completed about 80% of its travel before the sensor leaves the liquid. The difference in the amount of splashing is the assumed cause. The in-liquid voltage was somewhat larger at a given sensor current than the voltage obtained with horizontal sensor leads.

The new sensor holder was built to reduce splashing, in the hope that it would help to eliminate stray transitions. The result was a definite degradation of the performance achieved with the original holder. The change to the vertical lead orientation may have more than negated any improvement that the reduced splashing might have introduced. Further study of mounting effects is warranted.

When LVDG was tested in liquid nitrogen the signal ratio decreased and the response time increased. Figure 4 indicates that the change in resistance of LVDG between gaseous and liquid nitrogen cannot exceed a change from about 55 to 75 Ω . This includes a 35 Ω lead resistance. At 40 mA constant current through the sensor, a change from 2.8 V to about 2.05 V was observed in agreement with the change of R . The signal ratio, $V_l/V_g = 1.37$ is unchanged at 50 mA current. A four-lead measurement would improve this to a ratio of 2. A rapid cycle test of LVDG is shown in Figure 7 for a 50 mA current. Unlike the LH_2 tests, no spikes occurred in the LN_2 tests signifying a temporary return to the previous state.

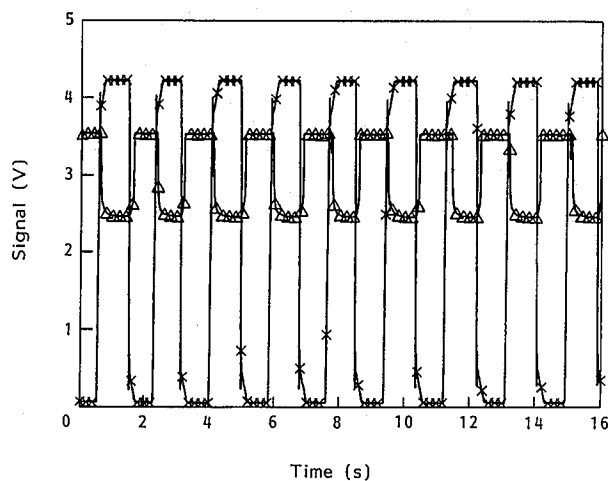


Figure 7 Output signal from LVDG cycled between LN_2 and GN_2 , Δ . Position sensor voltage, x. Leads horizontal, $I = 50$ mA, every 100th data point shown

Table 1 Response time of LVDG in LN₂

Current (mA)	Power (mW) in liq.	Out-to-in (ms) Avg.	In-to-out (ms) Avg.	Sum (ms)	Relative holder position
40	64	57	154	211	High
40	64	48	308	356	Low
50	100	118	101	219	High
50	100	106	107	213	Low

The response times were much longer for LN₂, Table 1, than for LH₂. This is not unexpected since both the heat capacity of the sensor and the liquid film is greater. At a current of 50 mA, the in-to-out response is equal to the out-to-in response. The sum of the response times for one cycle is less for 40 mA mainly because the out-to-in response was about half that of 50 mA. This suggests that the heat capacity of the sensor is the determining factor in the response time.

The in-to-out response time for the LVDG at 40 mA varies from as little as 40 to more than 640 ms. At 50 mA the response time scatter was from 27 to 215 ms. The out-to-in response time scatter was much less at both currents, 31 to 87 ms at 40 mA and 78 to 154 ms at 50 mA. Splashing of the liquid when the holder departs the surface may account for the greater variation in the in-to-out response times.

The position of the sensor holder relative to the liquid surface appears to cause a difference in the responses of the sensor at 40 mA as shown in Table 1. The splashing is less when the liquid level is high. The in-to-out response time is slower then. In one test the sensor even failed to respond a few times before the sensor returned to the liquid, meaning a response time delay of as much as 1.5 s.

At 50 mA, no difference in response time with liquid height was evident. The sensor holder used for these tests probably represents the worst case for a fixed sensor in terms of splashing. A new sensor holder was built to reduce the splashing to ascertain further the effects of splashing. This holder was used for the last LH₂ and LN₂ test and may have contributed to the differences in sensor behaviour between vertical and horizontal lead configurations.

The large change in sensor resistances and the short response time make the LVDG sensor the best of those tested for use in LH₂. The sensor had the fastest response in LN₂ to withdrawal from the liquid. The response is slower and the signal change reduced from that in LH₂. It is possible that a stronger signal could be obtained for LVDG in LN₂ if the doping of the silicon sensor is increased.

The sensor is unfortunately not now commercially available. One of the objectives of this project is to develop a commercial source for this sensor.

Optical L – V sensors

Of the non-thermal methods of detecting liquid – gas interfaces, some optical sensors were tested because they could be made small enough to approximate a point sensor.

Burgeson and Richards^{1,2} have already demonstrated that an optical sensor can be used as an L – V sensor for LH₂. The unit they tested transmitted different magnitudes of light depending on whether reflecting surfaces are wetted with liquid. This original optical level sensor required a light bulb and photodetector in the vessel containing the liquid. The objective in these present tests was to drive a sensor of the same type with the light source and detector outside the vessel and coupled to the sensor by fibre optic cables.

A commercially available level sensor of this design has been tested. This sensor consists of a prism that is a 90° cone, Figure 8. The amount of light transmitted from the source to the detector depends on whether the liquid is present. This sensor functioned well when tested in LN₂ but could not be adjusted to detect LH₂. The smaller light intensity change produced by the small index of refraction of LH₂ was apparently insufficient to overcome the hysteresis in the circuit driving the relay. The direct output of a diode detector connected to the output fibre changed reliably from 0.5 V in liquid to 0.75 V in gas.

Two optical level sensors operating on the same principle were built at NIST. These units, shown in Figures 9 and 10 differed from the commercial unit in that

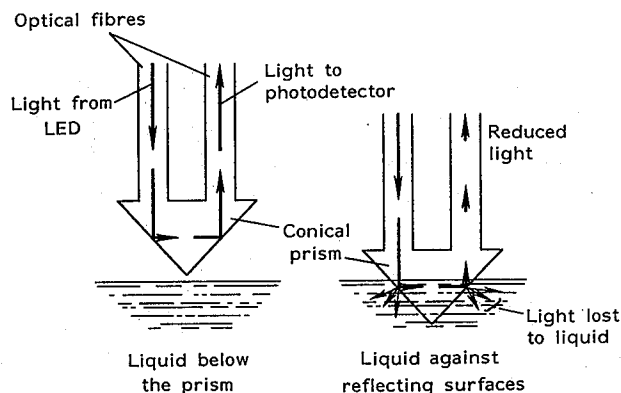


Figure 8 Diagram showing operating principle of the commercially available optical sensor for liquid – vapour interfaces

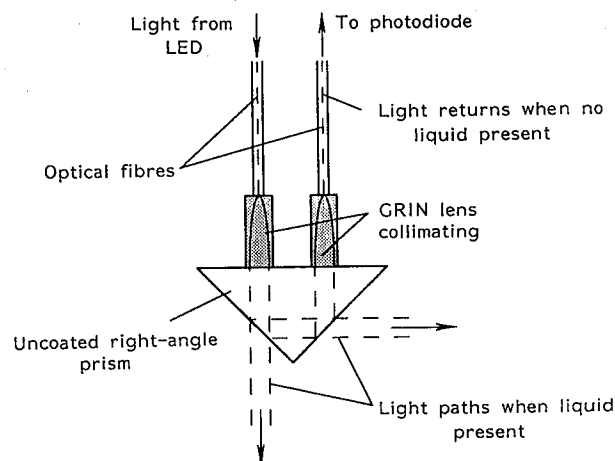


Figure 9 Diagram of a two-lens modification of the optical interface sensor

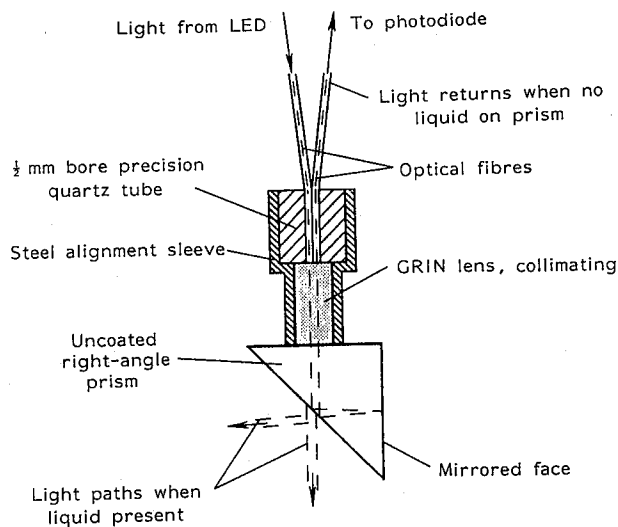
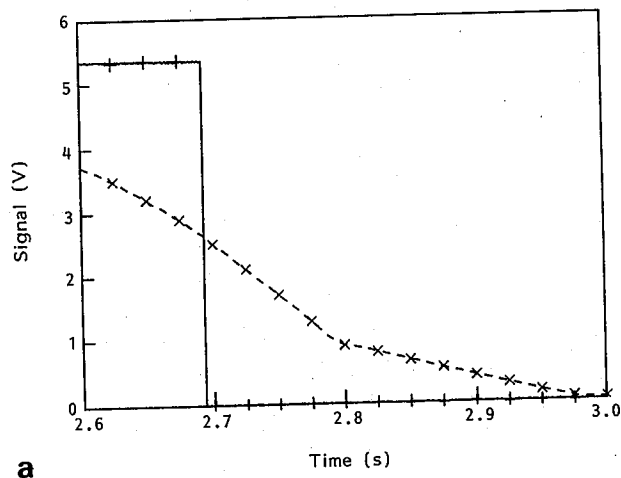
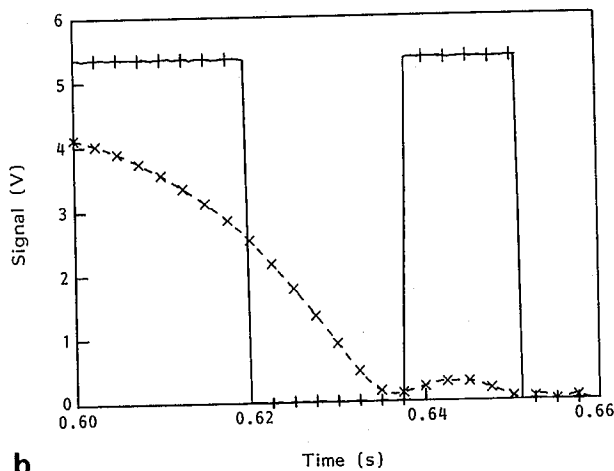


Figure 10 Diagram of the single lens modification of the optical interface sensor

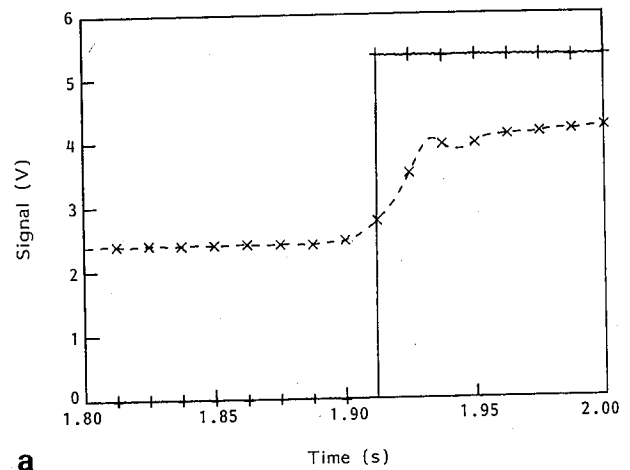


a

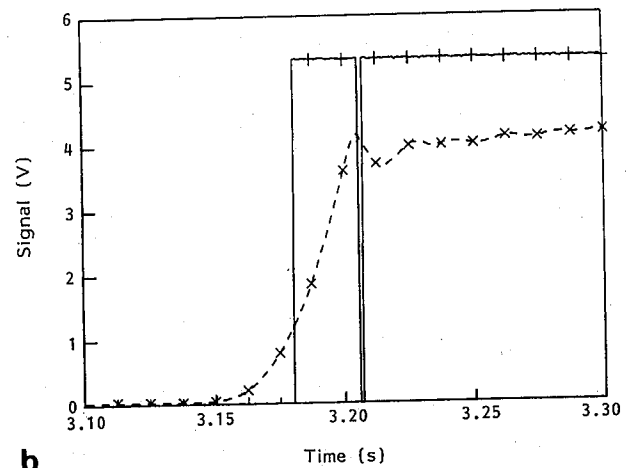


b

Figure 11 +, Output signal from the commercial optical level sensor for a: (a) slow transition, (b) fast transition, from GN_2 to LN_2 . x, Position sensor. Every (a) 50th, (b) 5th data point shown



a



b

Figure 12 +, Output signal from the commercial optical level sensor for a: (a) slow transition; (b) fast transition from LN_2 to GN_2 . x, Position sensor. Every 25th data point shown

graded index (GRIN) lenses collimated the light into the prism and refocused it from the prism into the fibre transmitting to the detector. Also, the light reflected from planar faces of the prisms rather than from conical faces.

The sensor shown in Figure 9 uses one lens to collimate the light into the prism and a second to refocus the light back into the detector fibre. A signal change of 7 to 1 between GH_2 and LH_2 was obtained from this sensor. The resolution was estimated to be 3 mm in the vertical direction. If the sensor assembly were tilted 90° the resolution is determined by the distance between the fibres plus a major part of the collimated beam diameter. At the minimum, this approaches twice the lens diameter, or 4 mm.

The sensor shown in Figure 10 uses only one lens to couple the fibres to the prism. The light reflects off the mirrored surface and follows approximately the incident path back to the exit fibre. The fibres are offset from the axis of the lens by their radius and placed so the light entering from one fibre is focused back into the other. A gas-to-liquid signal ratio of 7 to 1 was obtained with this lens for H_2 also. The resolution of the liquid surface position by this sensor varies from about 0 to

something less than the beam diameter depending on the angle between the liquid surface and the unsilvered reflecting face.

Only one model of each was built and tested. No special materials were used. Conventional epoxies were used to hold the assemblies together. The sensor assemblies did not fail after repeated cycles between ambient and 77 or 20 K.

The response time of only the commercial optical sensor was tested and only in water and LN_2 . The average response times both entering and leaving the liquid were 3 ms, while the maximum response time observed was 6 ms in both entering and leaving. The electronic response time had to be well below 1 ms because, even at a 1 kHz reading rate, no data point was ever recorded intermediate between the in and the out signals.

Figures 11a and b show two transitions of the commercial sensor into the liquid. A single sharp step resulted for a lower velocity into the liquid, Figure 11a. A fast transition, Figure 11b, resulted in some bouncing of the signal back to the out reading. These often correlate with bouncing of the probe against the air cylinder stop. Probably, cavitation at the probe tip causes this behaviour.

Single, sharp transitions occur when the sensor is withdrawn from the liquid, Figure 12a. Sometimes a momentary return to the liquid value is observed, Figure 12b. Occasionally the sensor anticipates the withdrawal from the liquid. Both effects are probably caused by cavitation at the reflecting faces. The prism face is the trailing surface when the sensor is withdrawn rapidly from the liquid. Bubbles from the Dewar walls can float up to the reflecting faces of the sensor and cause a momentary gas signal.

The optical L–V sensor is fast and introduces much less heat into cryogenic vessels than resistive L–V sensors. The optical sensor can be reduced in size from those tested here, but it is unlikely that an optical sensor can be made as small as LVDG. A question yet to be answered concerning the optical sensor is whether the reflecting properties of the surfaces will be altered by contamination over time.

The speed of optical sensors is determined entirely by the interaction of the liquid and sensor, not by any of the physical properties of the sensor only, thus the response time is short. The change of signal is large. If the supporting structure is ignored, LVDG should perturb a passing liquid surface less than the optical sensors because of its much smaller size.

Acknowledgements

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